On the Minimum Induced Drag of Wings

Albion H. Bowers

NASA Neil A. Armstrong Flight Research Center

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Birds

Wandering Albatross

Bird Flight

- Soaring Land Birds:
  - lower aspect ratio (~8)
  - operate at/near min sink (loiter)
  - operate in more turbulent air
  - tend to have larger tails
  - condors, vultures, eagles, hawks, falcons, kites

- Soaring Sea Birds:
  - higher aspect ratios (~12-16)
  - operate at/near max L/D (range)
  - operate in more predictable wind field
  - tend to have smaller tails
  - albatross, petrels, shearwaters, frigates, gulls, terns

Themes

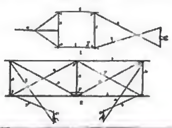
- Requirements & Concepts
  - The boxes we think inside of
  - requirements & assumptions
  - ideas, concepts, & solutions

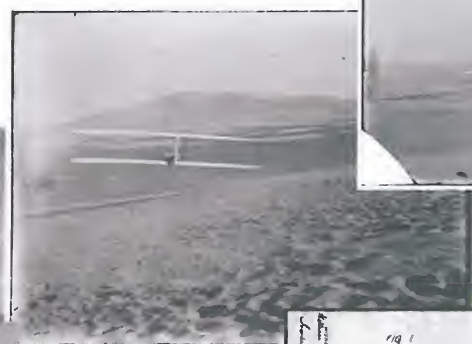
- If an alternative were found to our current thinking, could we let go of our preconceived notions to see the alternative?

- Models, sUAS, and Research Aircraft
  - line are blurring between classes
  - easy to create solutions in small scale aircraft today
  - easy to gather incredibly accurate and complete data sets now

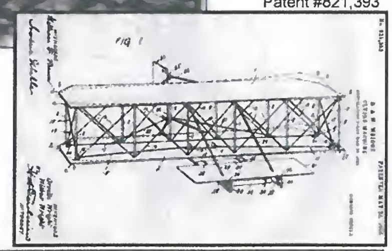
Wilbur & Orville Wright

- Flying experiments 1899 to 1905





Patent #821,393



Breguet Range Equation

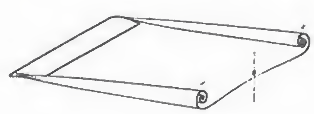
- Range
  - propulsive efficiency
  - specific fuel flow
  - L/D
  - weight fraction

$$R = \frac{\eta_j}{c_p}\frac{C_L}{C_D} ln \frac{W_1}{W_2}$$

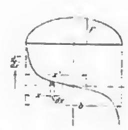
Spanload, Downwash, Induced Drag

- All wings dictate 3 solutions
- Spanload
- Downwash
- Induced Drag

Prandtl Lifting Line Theory

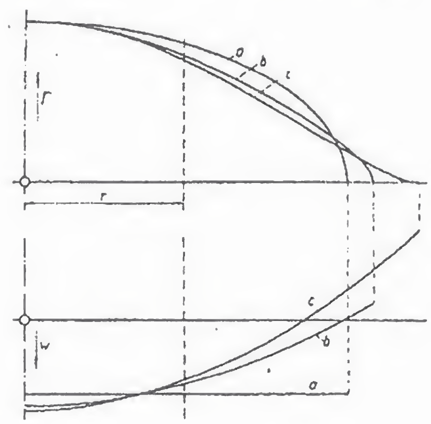


- Prandtl' s "vortex ribbons"



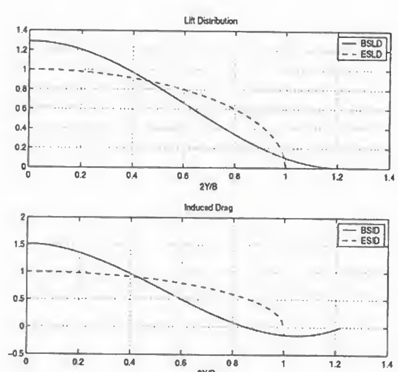
- Elliptical spanload for a given span (1920)
- "the downwash produced by the longitudinal vortices must be uniform at all points on the aerofoils in order that there may be a minimum of drag for a given total lift." y = c

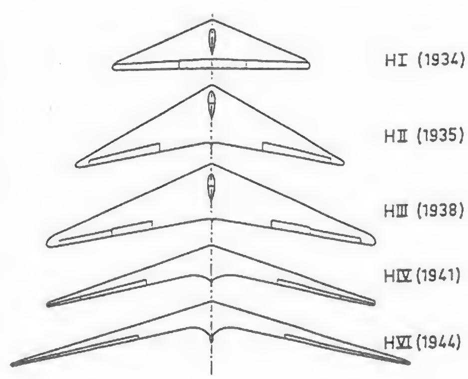
Minimum Induced Drag & Bending Moment



- Prandtl (1932)
  Constrain minimum induced drag
  Constrain wing root bending moment
  22% increase in span with 11% decrease in induced drag

Horten Applies Prandtl's Theory

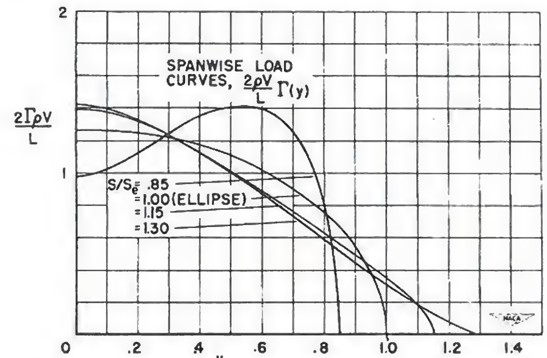




Horten Sailplanes

- Horten Spanload (1934-1954)
  use twist to achieve spanload
  induced thrust at tips
  wing root bending moment

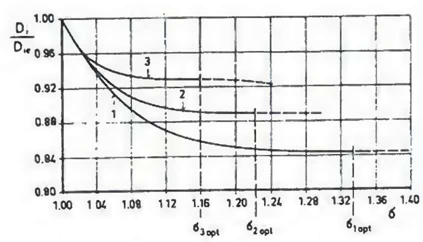
Jones Spanload



- Minimize induced drag (1950)
  Constrain wing root bending moment
  30% increase in span with 17% decrease in induced drag

- "Hence, for a minimum induced drag with a given total lift and a given bending moment the downwash must show a linear variation along the span." y = bx + c

Klein and Viswanathan

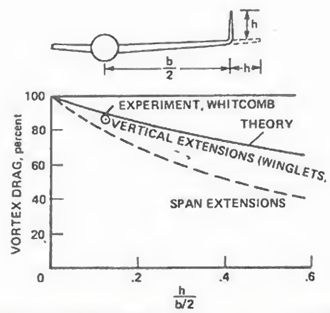


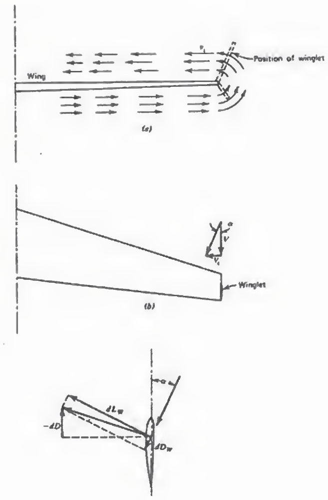
- Minimize induced drag (1975)
  Constrain bending moment
  Constrain shear stress
  16% increase in span with 7% decrease in induced drag

- "Hence the required downwash-distribution is parabolic." $y = ax^2 + bx + c$

Winglets

- Richard Whitcomb's Winglets
  - induced thrust on wingtips
  - induced drag decrease is about half of the span "extension"
  - reduced wing root bending stress





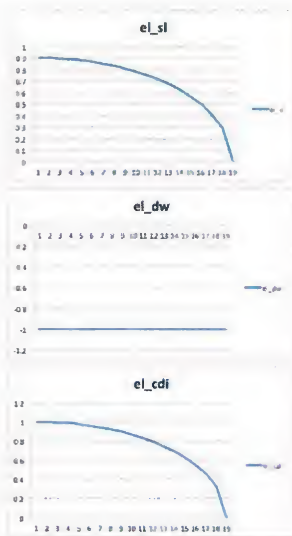
Spanload Summary

- Prandtl/Munk (1914)
  Elliptical
  Constrained only by span and lift
  Downwash: y = c
- Prandtl/Horten/Jones (1932)
  Bell shaped
  Constrained by lift and bending moment
  Prandtl: theory, Horten: twist, and Jones: planform
  Downwash: y = bx + c
- Klein/Viswanathan (1975)
  Modified bell shape
  Constrained by lift, moment and shear (minimum structure)
  Downwash: $y = ax^2 + bx + c$
- Whitcomb (1975)
  Winglets
- Summarized by Jones (1979)
- Bell is 11% more efficient for same structural weight

Prandtl(1920) vs Prandtl(1932)

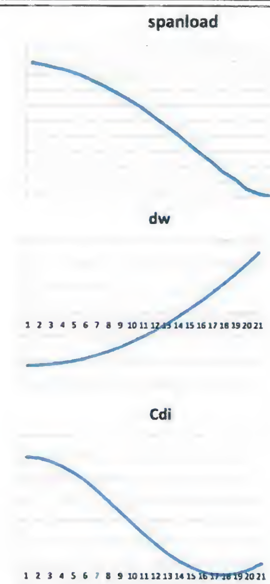
Prandtl
1920

Elliptical
Spanload



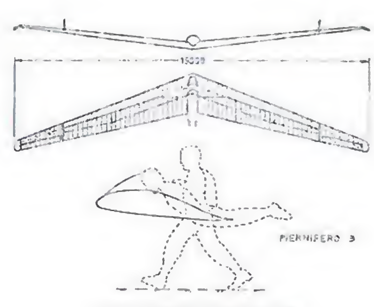
Prandtl
1932

Bell
Spanload



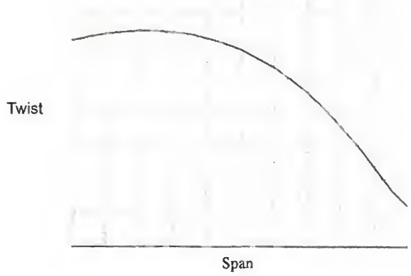
Horten H Xc Example

- Horten H Xc footlaunched ultralight sailplane 1950

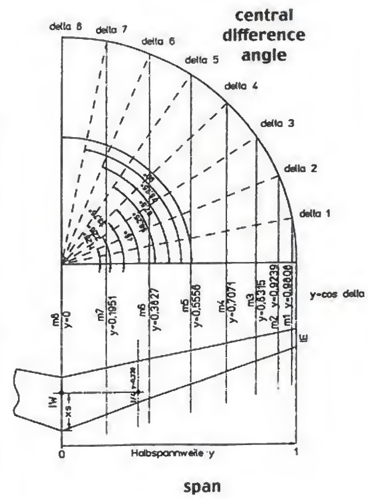


Calculation Method

- Taper
- Twist
- Control Surface Deflections
- Central Difference Angle



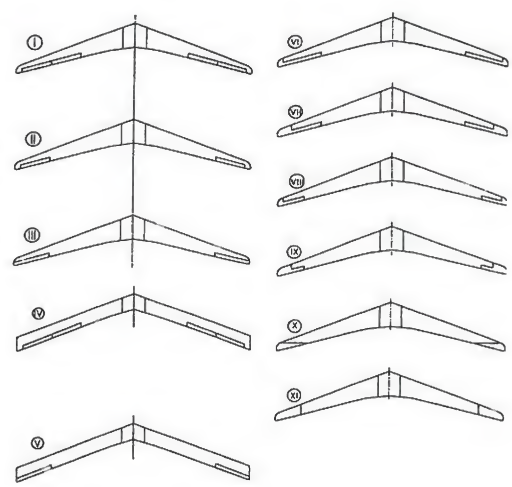
R0	8.3274
R1	8.5524
R2	8.7259
R3	8.8441
R4	8.9030
R5	8.8984
R6	8.8257
R7	8.6801
R8	8.4565
R9	8.1492
R10	7.7522
R11	7.2592
R12	6.6634
R13	5.9579
R14	5.1362
R15	4.1927
R16	3.1253
R17	1.9394
R18	0.6589
R19	-0.6417
R20	-1.6726



Dr Edward Uden's Results

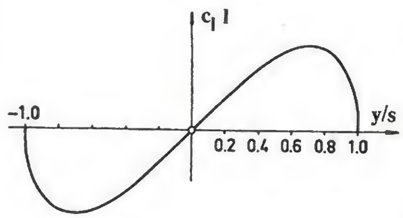
- Spanload and Induced Drag
- Elevon Configurations
- Induced Yawing Moments

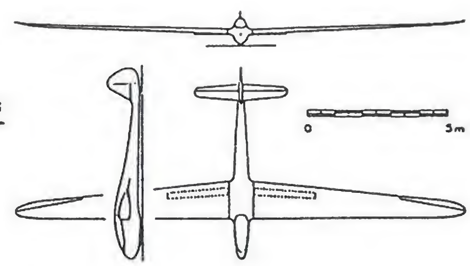
Elevon Config	Cn∂a	Spanload
I	-.002070	bell
II	.001556	bell
III	.002788	bell
IV	-.019060	elliptical
V	-.015730	elliptical
VI	.001942	bell
VII	.002823	bell
VIII	.004529	bell
IX	.005408	bell
X	.004132	bell
XI	.005455	bell



Elliptical Half-Lemniscate

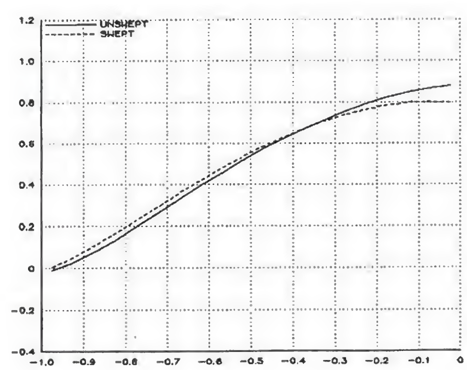
- Minimum induced drag for given control power (roll)
- Dr Richard Eppler: FS-24 Phoenix





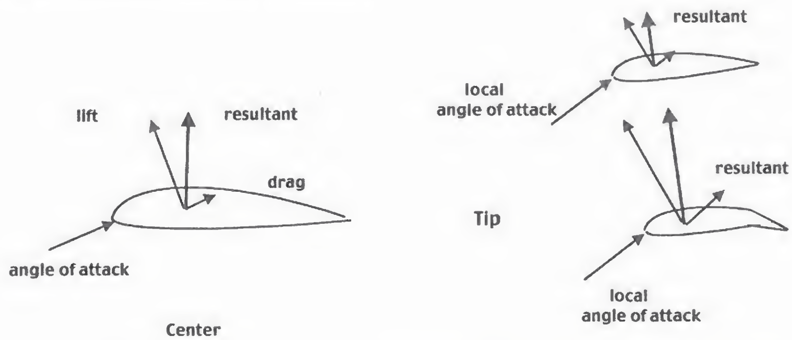
"Mitteleffekt"

- Artifact of spanload approximations
- Effect on spanloads
  increased load at tips
  decreased load near centerline
- Upwash due to sweep unaccounted for



Horten H Xc Wing Analysis

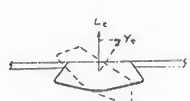
- Vortex Lattice Analysis
- Spanloads (longitudinal & lateral-directional) - trim & asymmetrical roll
- Proverse/Adverse Induced Yawing Moments
  handling qualities
- Force Vectors on Tips - twist, elevon deflections, & upwash
- 320 Panels: 40 spanwise & 8 chordwise



How do birds turn?

- Proverse/adverse yaw only solves constant turn rate problem
- Roll/yaw acceleration needed to initiate turns
- Need for a tail arises for maneuvering ("agility")

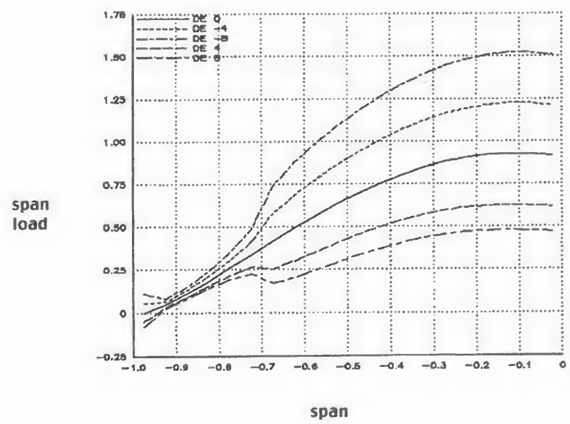
- "First the tail is tilted downward on the side away from the direction of the turn...Perhaps the tail functions as a rudder in starting the turn..." (California Condor, Koford, 1950)
- "...the tail was loaded upward and the same clockwise tail rotation produced a right force, thus a left turn..." (Flight of Ravens, Hoey, 1992)



(b) UP-LOADED TAIL
(AFT CG)

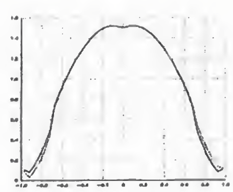
Symmetrical Spanloads

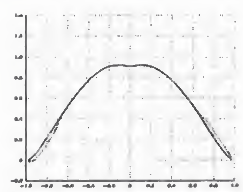
- Elevon Trim
- CG Location

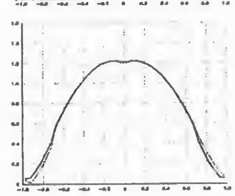


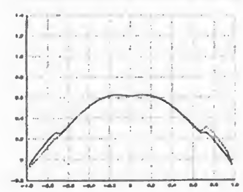
Asymmetrical Spanloads

- Cl∂a (roll due to aileron)
- Cn∂a (yaw due to aileron)
  induced component
  profile component
  change with lift
- Cn∂a/Cl∂a
- CL(Lift Coefficient)
  Increased lift:
   increased Clβ
  increased Cnβ*
  Decreased lift:
   decreased Clβ
  decreased Cnβ*

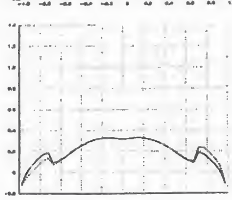








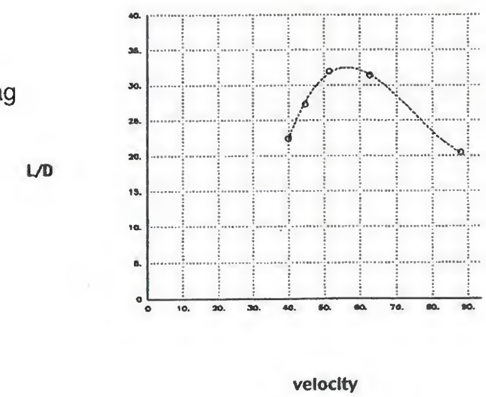
CL	Cl	Cn
.966	.01384	.00055
.774	.01384	.00037
.582	.01345	.00021
.390	.01384	.00003
.198	.01345	-.00015



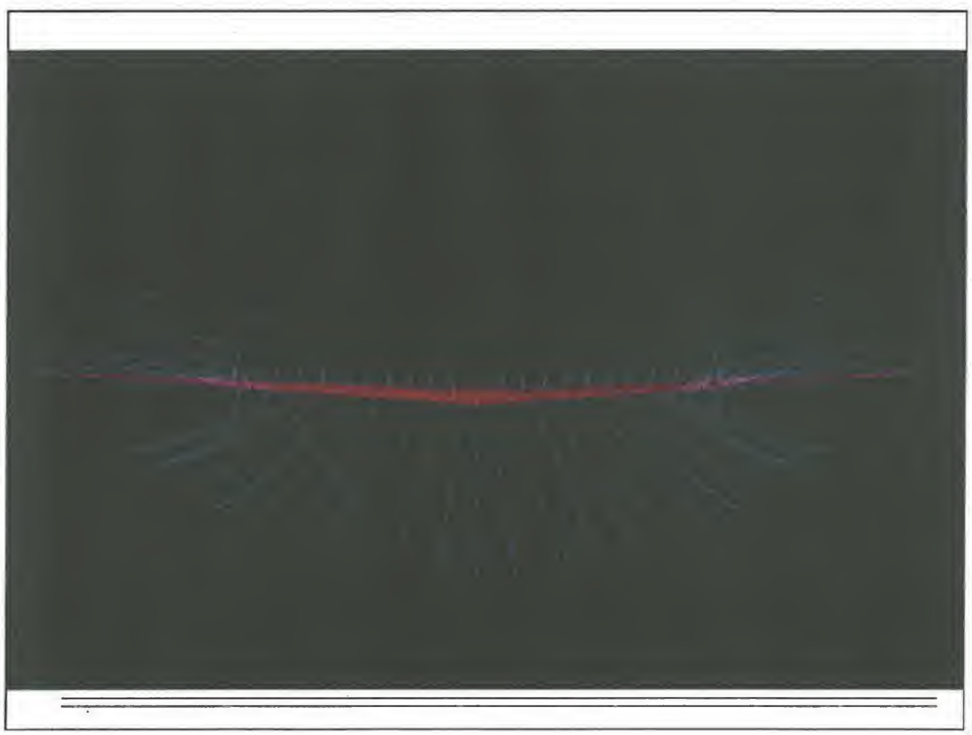
Performance Comparison

- Max L/D: 31.9
- Min sink: 89.1 fpm
- Does not include pilot drag

- Prediicted L/D: 30
- Predicted sink: 90 fpm



Mike Allen

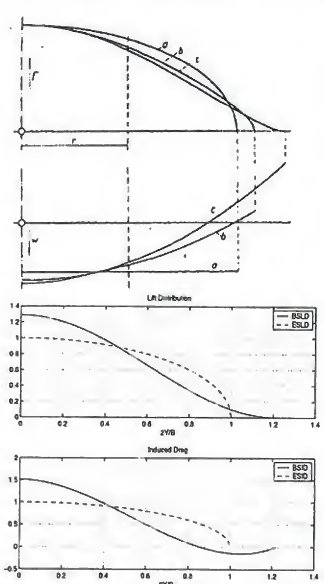


Spanload

Prandtl/Horten/Jones Spanload: Birds

- Bell Shaped Span Load is equivalent to bird span load
- Maximum performance (minimum drag)
- Flight mechanics are the same (proverse yaw)
- Minimum structure (minimum weight)
- Solve three problems minimum drag, flight mechanics, and minimum structure with one solution

Prandtl, Horten, Jones, and Birds



Experiment Design: PRANDTL-D

- How could this be proven to be true?

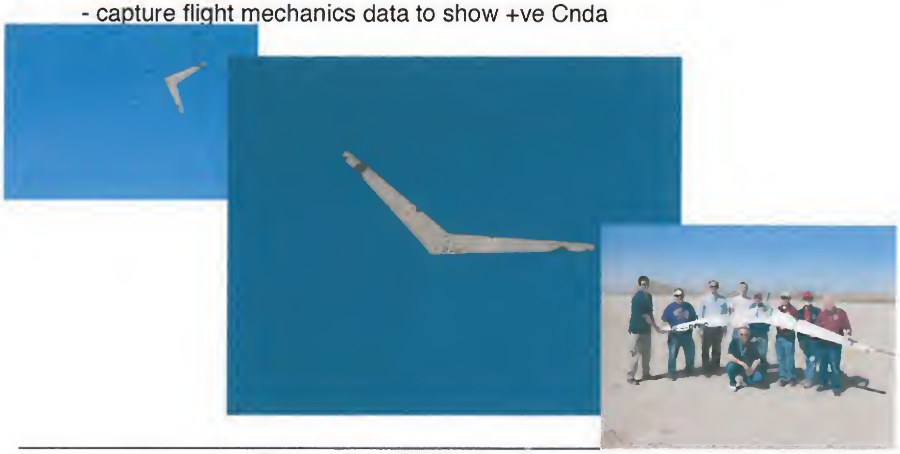
- If Prandtl (1932) is correct, the spanload must be correct
- If the spanload is correct, then the upwash/downwash must be correct
- If the upwash/downwash is correct, then proverse yaw is true
- If proverse yaw is true, Cnda is +ve

- Ergo, prove 2 things:
  - proverse yaw is true
  - Cnda is +ve

- Primary Research AerodyNamic Design To Lower Drag (PRANDTL-D)

PRANDTL-D

- Primary Research AerodyNamic Design To Lower Drag
- sUAS (12.5 ft span, 15 lb, instrumented)
  - no differential control, 2 surfaces
  - prove proverse yaw
  - capture flight mechanics data to show +ve Cnda



PRANDTL-D Proverse Yaw?

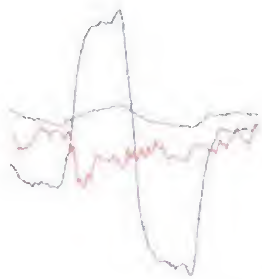
What would Proverse Yaw look like?

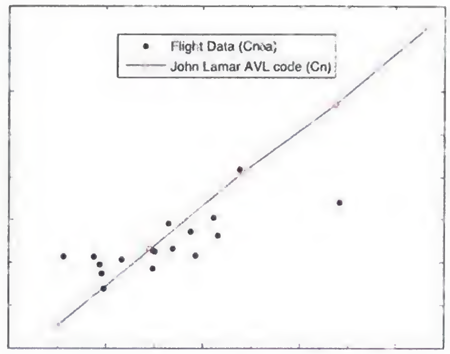
Flight Data

- Measurement of proverse yaw would be the final hurdle to achieve
- Icing on the cake: measure Cnda (yawing moment due to aileron deflection)
- NOT ONE SECOND OF FLIGHT DATA TO PROVE ANY OF THIS IS TRUE

Proverse Yaw

- ...until June 26th, 2013
- Roll and Yaw are the same sign
- From Uden: Cnda is +ve
- uncertainty





Inertias; configuration changes, turbulence, and slope of Cnda

PRANDTL-D Aircraft

Control of Yaw

- You Have Three Choices:
- 1/ drag a vertical tail around with you all the time to create a yawing moment
- 2/ manipulate drag at the wing tips to control yaw

} Current Design Options

-OR-

- 3/ manipulate **THRUST** at the wing tips to control yaw

Concluding Remarks

- Birds as as the first model for flight
- Applied approach gave immediate solutions, departure from bird flight
- Eventual meeting of theory and applications (applied theory)
- Spanload evolution (Prandtl/Munk, Prandtl/Horten/Jones, Klein & Viswanathan, & Whitcomb)
- Solve performance, structure and control with ONE solution!
- 12.5% increase in L/D, ~13.4% increase in prop efficiency, 20-30% decrease in drag eliminating the tail, ~43-62% reduction in total aero efficiency
- Assumptions and Solutions
- The Wrights disintegrated the flight of birds, and Prandtl/Horten/Jones reintegrated the flight of birds...
- Thanks: Red Jensen, Brian Eslinger, Hayley Foster & Steve Craft, Dr Bob Liebeck, Nalin Ratnayake, Mike Allen, Walter Horten, Georgy Dez-Falvy, Rudi Opitz, Bruce Carmichael, R.T. Jones, Russ Lee, Bob Hoey, Phil Barnes, Dan & Jan Armstrong, Dr Phil Burgers, Ed Lockhart, Andy Kesckes, Dr Paul MacCready, Reinhold Stadler, Dr Edward Uden, Dr Karl Nickel, & Jack Lambie

NASA Aero Academies & Others

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  - Eric Gutierrez, Louis Edelman, Kristyn Kadala, Nancy Pinon, Cody Karcher, Andy Putch, Hovig Yaralian, Jacob Hall

- 2012 NASA Aero Academy
  - Steffi Valkov, Juliana Plumb (Ulrich), Luis Andrade, Stephanie Reynolds, Joey Wagster, Kimmy Callan, Javier Rocha, Sanel Horozovic, Ronalynn Ramos, Nancy Pinon

- Mike Allen, Alex Stuber, Matt Moholt, Dave Voracek, Ross Hathaway, Brian Eslinger, Oscar Murillo, Lesli Monforton, Red Jensen, Aamod Samuel, Brad Neal, Brad Flick, Chris Acuff, Rick Howard (NPS), Marko Stamenovic, Jim Murray, Nalin Ratnayake, Eric Nisbet, Jeromy Robbins, Nelson Brown, Curtis Stump, Andrew Burrell, Anthony MacPherson, Brian Taylor, Chris Miller, Victor Loera, Cameron Law, Koen vander Kerckhove, Russ Lee, Reinhold Stadler, Edward Uden, Paul MacCready, Karl Nickel, Walter Horten, Diego Roldan Knollinger

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Red Jensen: pilot, engineer, technician

NASA Aero Academy 2013

NASA Aero Academy 2012

If you want to build a ship, don't drum up people to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea…

- Antoine de Saint-Exupery

Questions?

PRANDTL-D

- Videos

  - TEDxNASA 2011
  http://www.youtube.com/watch?v=223OmaQ9uLY

  - NASA Aero Academy 2013
  http://www.youtube.com/watch?v=Hr0I6wBFGpY